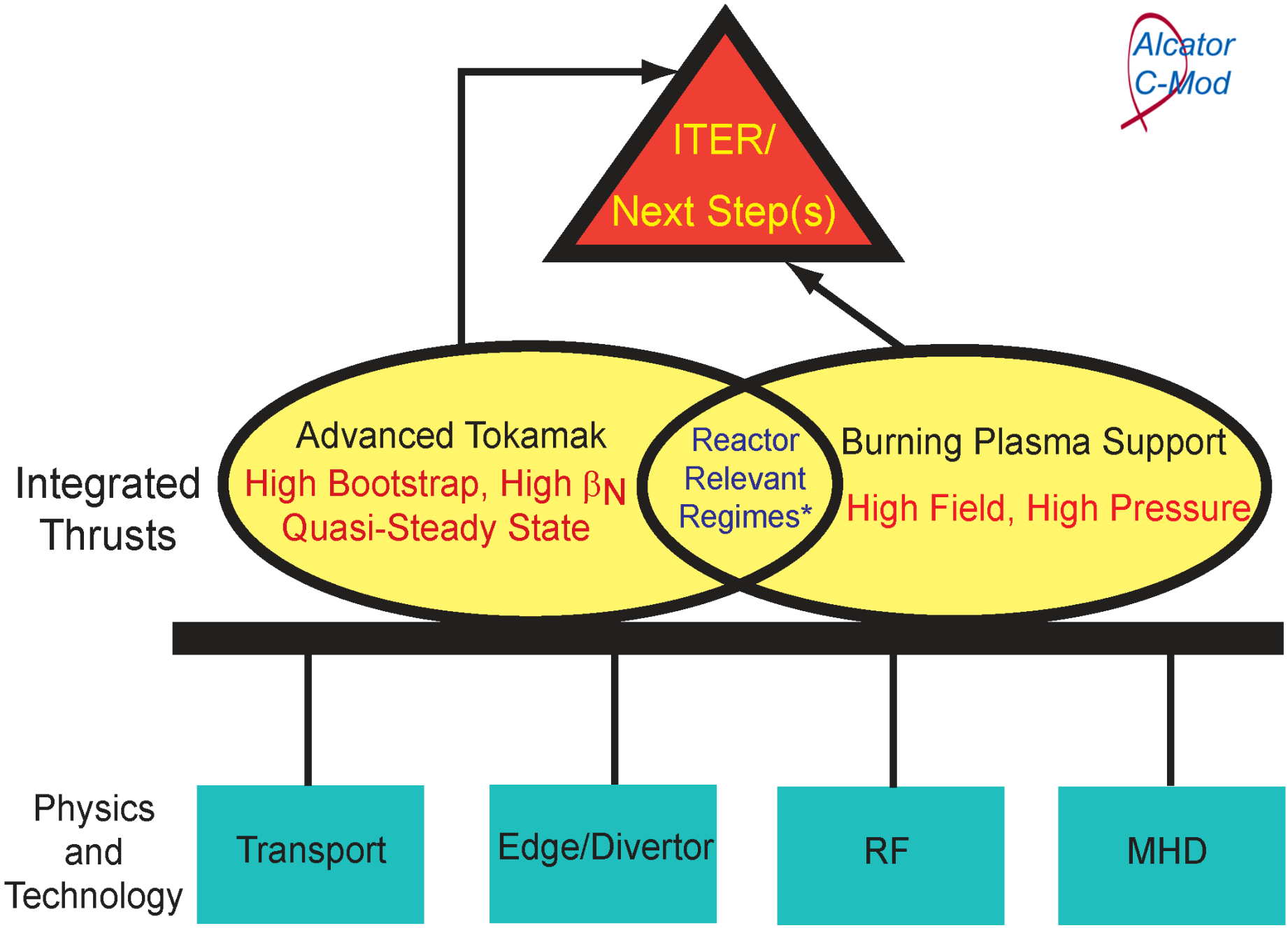
Alcator C-Mod
Highlights, Plans, Budget and Schedule

OFES Budget Planning Meeting

March 17, 2004

E. S. Marmar

for the Alcator Group



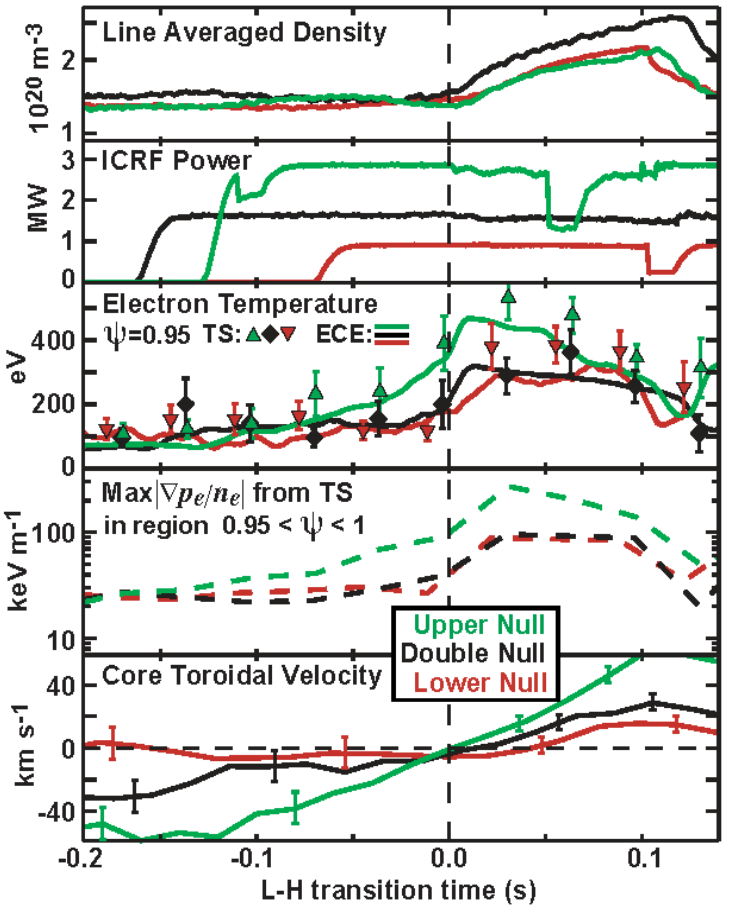
*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive

Research Highlights

- Spontaneous rotation, momentum transport
  - Relations among SOL and core rotation, topology and H-mode threshold
  - Momentum transport in different regimes (L, H, EDA)
- Edge turbulence
  - Scale length dependence on ν^*, detailed imaging of coherent structures and comparisons with models
  - Ballooning nature confirmed – asymmetry drives SOL flows
- Error Fields and Locked Modes
  - Sensitivity, size & field scaling (ITER), control with external coils
- Progress understanding H-mode pedestal regulation through improved diagnosis and modeling
  - Radial localization of QC mode

Topology, Rotation, H-Mode Threshold

Linked



B. LaBombard, et al., submitted to PRL (2004)

Research Highlights (continued)

- Dimensionless identity experiments suggest plasma physics dominance of pedestal structure
- Control of ITB location demonstrated
- ITB modeling elucidates mechanisms of formation (ITG suppression) and regulation (TEM modes)
- ICRF Mode Conversion at the Ion-ion Hybrid Layer (Experiment and Modeling)
- Current-drive phased operation of 4-strap antenna
  - Mode conversion current drive and heating
- Alfven Modes studied
  - Stable modes probed with active MHD spectroscopy
  - Unstable cascades observed and modeled

Budget Profiles (k$)

Alcator C-Mod

Appropriation Guidance

Institution	FY04	FY05	FY06
MIT	19,727	18,972	18,972
PPPL	2,070	2,050	2,050
U Texas	425	425	425
LANL	97	100	100
National Project Total (run weeks)	22,269 (19)	21,547 (14)	21,547 (12)
5 Year Proposal (run weeks)	*25,250 (25)*	*27,610 (25)*	*28,710 (25)*

Collaborations are Significant in all Aspects of the Program

Domestic Institutions

Princeton Plasma Physics Lab
U. Texas, Austin
U. Alaska
UC-Davis
UC-Los Angeles
UC-San Diego
Dartmouth U.
GA
LLNL
Lodestar
LANL
U. Maryland
MIT-PSFC Theory
Notre Dame U.
ORNL
SNLA
U. Wisconsin

International Institutions

Australian National University
Budker Institute, Novosibirsk
C.E.A. Cadarache
Chalmers U., Sweden
C.R.P.P. Lausanne
Culham Lab
IGI Padua
IPP Greifswald
IPP Garching
JET/EFDA
JT60-U, JFT2-M/JAERI
KFA Jülich
KFKI-RMKI Budapest
LHD/NIFS
Politecnico di Torino
U. Toronto

Theory and Modeling Collaborations

- Transport,Turbulence and MHD
  - Xu, Nevins, Rognlien, Umansky, R. Cohen: EDA H-mode QCM, Edge Fluctuations (BOUT simulations)
  - Carreras, Antar : SOL turbulence analysis, L-H dynamics
  - Guzdar: L-H threshold theory
  - Hallatschek and Rogers: Theory and modeling
  - Diamond: Theory
  - Mikkelsen, Dorland: Critical gradient – Non-linear stability
  - Redi, Ernst, Bravenec, Dorland: GS2 microturbulence modeling
  - Bateman and Kritz: Baldur transport simulations
  - McCune, C.K. Phillips: TRANSP
  - Chang, Chan, Coppi, Perkins, Shaing, White: Transport, RF induced rotation
  - Huysmans, Wright: TAE modeling (CASTOR)
  - Boswell, Sharapov, Breizman, Berk: Alfven cascades
  - Brennan: NTM 3-D MHD modeling
- Impurity and Particle Dynamics
  - Stangeby, Lisgo, Elder: OSM-Eirene divertor plasma and neutral modeling
  - Stotler: DEGAS II neutral transport
  - Pigarov, Krasheninnikov: Edge atomic processes, 2-D edge transport modeling (UEDGE), Edge turbulence/structures
  - Catto, Helander, Fulop: Neutral effects on rotation
  - Parks: Pellet ablation dynamics
  - Fournier: Atomic physics modeling

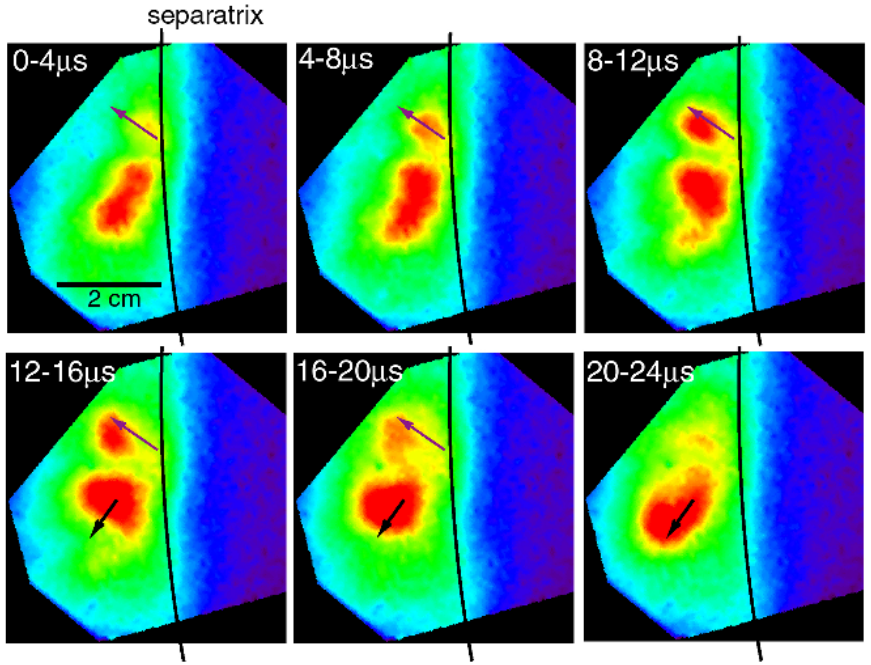
Theory and Modeling Collaborations (continued)

- ICRF
  - Jaeger, Myra and D'Ippolito: ICRF Flow Drive
  - Brambilla, Jaeger, D'Azevedo, Batchelor, J. Wright: Fast wave and Bernstein waves in toroidal geometry
  - McCune, C.K. Phillips, Okuda, Brambilla, J. Wright: Full-wave/Fokker Planck minority heating simulations
  - R. Maggiora (Torino): TOPICA modeling of antenna-plasma system
- Lower Hybrid
  - C.K. Phillips, Okuda, J. Wright: 2D full wave simulations
  - Peysson, Bers: Fokker Planck LHCD efficiency and distribution functions
  - Harvey, Imbeaux: 2D LHCD Fokker Planck simulations
  - Bernabei: Scenario development
  - Bernabei: Launcher design and coupling simulations
  - McCune, C.K. Phillips: Integration of ACCOME into TRANSP

PPPL Collaborations

- ICRF Physics and Technology (Schilling, Wilson, Hosea, Zweben, Brunkhorst)
- LHRF Physics and Technology (Bernabei, Wilson, Hosea, Schilling, Loesser)
- MSE (S. Scott)
- Edge Turbulence (Zweben)
- Fast particle dynamics (S. Scott, Zweben)
- X-ray spectroscopy (Bitter, Hill, Stratton)
- Single null/double null (Meade)
- Theory/modelling
  - Transport (Redi, Mikkelsen)
  - RF (C. Phillips)
  - Edge (Stotler)

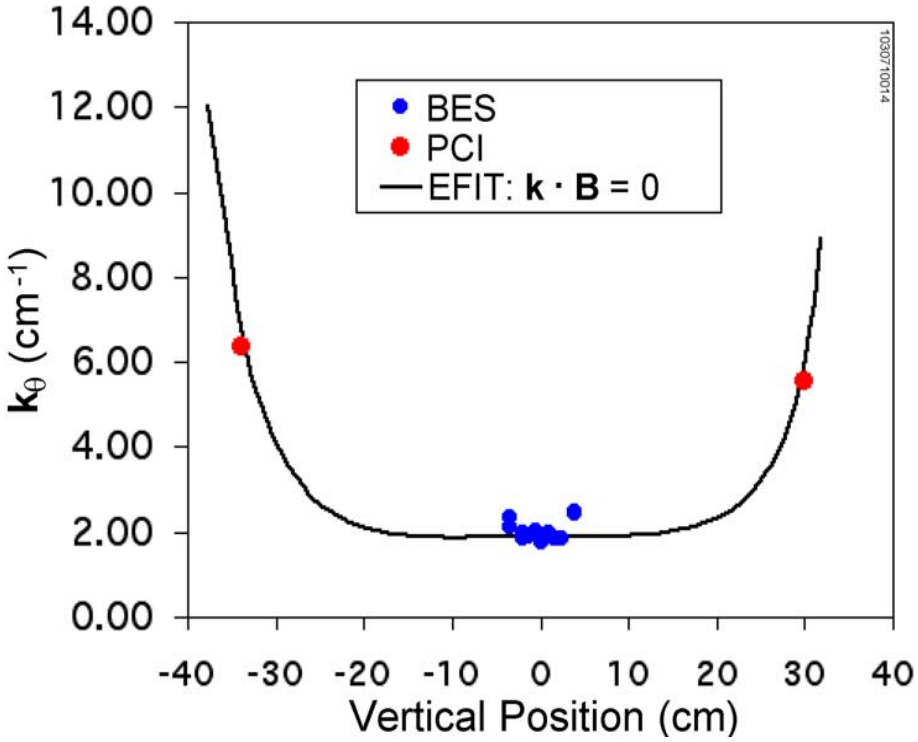
Ultrafast TV images of edge fluctuations show bursty transport



U. Texas FRC Collaborations

- High resolution ECE T_e profiles (P. Phillips, A. Lynn)
  - L_{Te}, Internal modes and fluctuations, QC-mode
- Beam Emission Spectroscopy (R. Bravenec, M. Sampsell)
  - Turbulence, QC-mode
- Charge exchange recombination spectroscopy (W. Rowan)
  - T_i and rotation profiles
- DNB operation (Rowan, Sampsell, Bravenec)

Measurements of QC-Mode k_θ from BES and PCI in reasonable agreement



Matt Sampsell, et al., APS-DPP 2003

Experimental Collaborations

- *Locked modes (LaHaye, GA; Hender, JET; Buttery, Culham)*
- *NTM Dimensionless Scaling with DIII-D (R. LaHaye, GA)*
- *Pedestal studies (Groebner, Osborne, GA; Suttrop, IPP Garching; Madison, Saibene, JET)*
- *EDA H-Mode (Madison, Saibene, JET; Oyama, JFT2-M; Suttrop, IPP Garching)*
- Alfven Eigenmode studies (Fasoli, CRPP; Boswell, MIT/JET)
- *ITB Physics (Stober, IPP Garching)*
- *ITER Hybrid Scenarios (Sips, IPP Garching)*
- *SOL Radial Transport (Kallenbach, IPP Garching; Whyte, U. Wisc.; Matthews, JET; Nakano, JT60-U)*
- Fluctuation Studies (Grulke, Endler, IPP Greifswald; Zoletnik, KFKI-RMKI Budapest)
- *Disruption Mitigation (Whyte, U. Wisc.)*
- IR Imaging (Wurden, Furno, LANL)
- X-Ray Imaging (Peysson, CEA-Cadarache)
- Polarimetry (Brower, Peebles, UCLA)
- Spectroscopy (May, LLNL; Graf, UC-Davis; Griem, U. Md.; Howard, ANU; Kondo, NIFS)
- ICRF Technology (Goulding, Ryan, Rasmussen, ORNL)
- Boron-Nitride tile analysis (Wampler, SNLA)
- Tungsten Plasma Facing Components (Ulrickson, SNLA)
- Diagnostic Neutral Beam (Valisa, IGI Padua; Ivanov, Budker Institute)
- *Tritium co-deposition (Whyte, U. Wisc.; Neu, IPP Garching)*
- MDSplus: Help maintain worldwide (currently >25 installations)

ITPA Joint Experiments

C-Mod has Prominent Role in Education

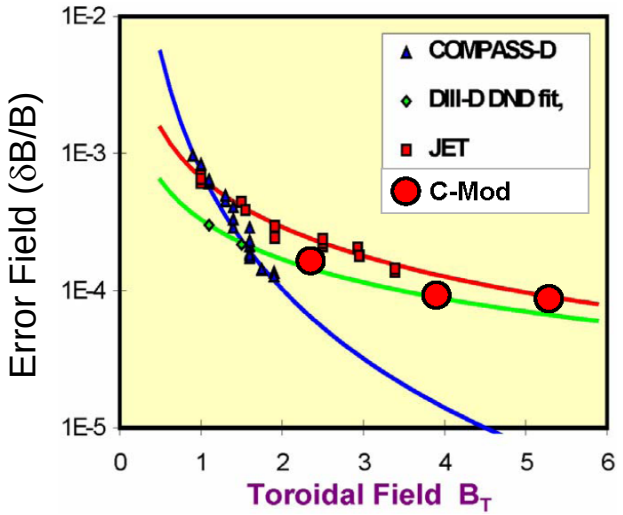
- Typically have ~20-25 graduate students doing their Ph.D. research on C-Mod
  - Nuclear Engineering, Physics and EECS (MIT)
  - Collaborators also have students working at the facility
  - Current total is 23
- MIT undergraduates participate through UROP program (~5 at any time)
- Host National Undergraduate Fusion Fellows every summer (3 in 2003)

C-Mod Addressing Critical ITER R&D

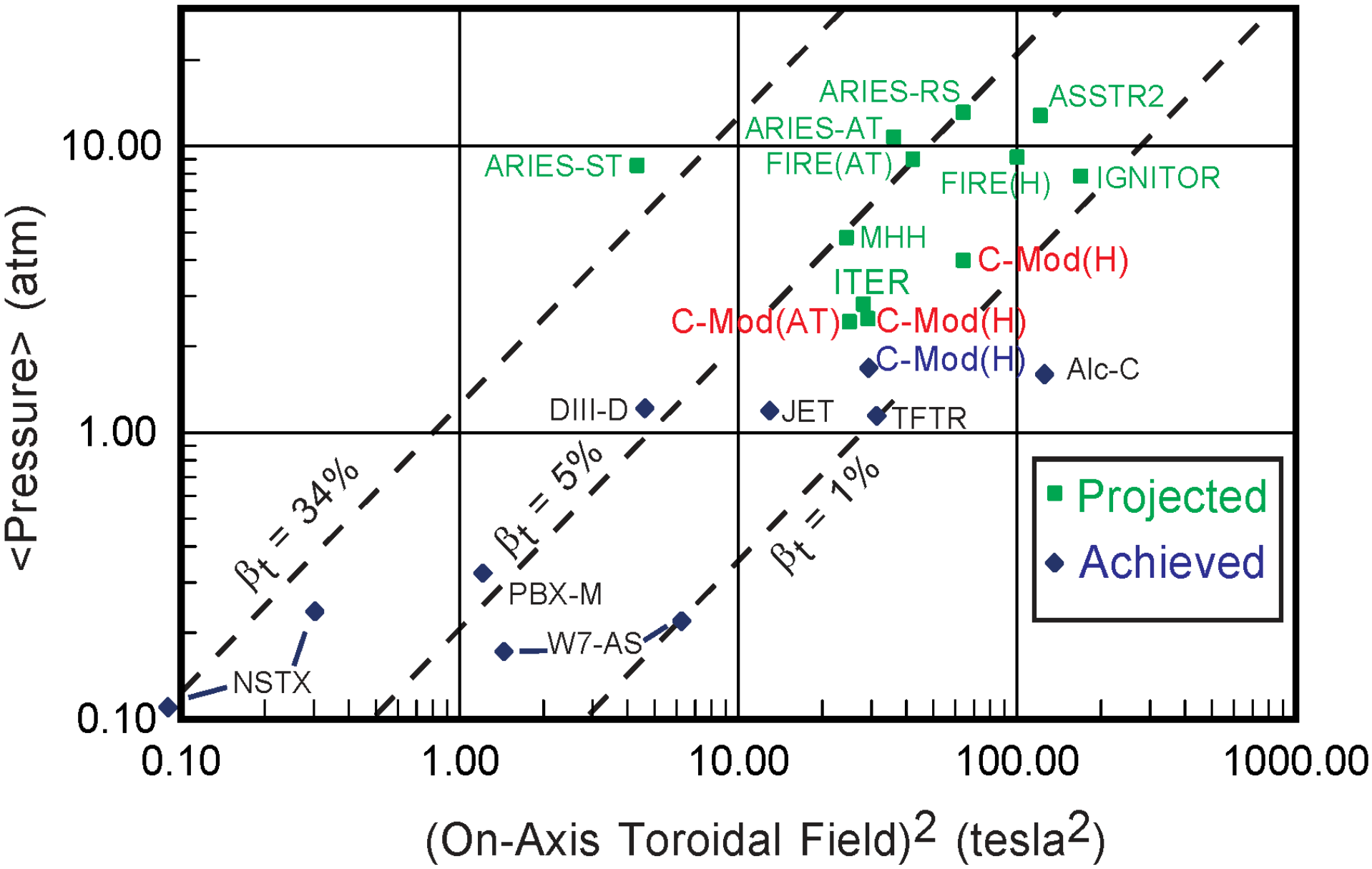
IPPA 3.2, 3.3

- Transport/Confinement with equilibrated electrons and ions
- Pedestal physics
  - small/no ELM regimes; scaling
- All metal plasma facing components
  - T retention, disruptions
  - Comparisons of molybdenum and tungsten
- Disruption Mitigation in high pressure plasma
- Rotation in the absence of direct momentum input
  - H-Mode dynamics; RWM stabilization
- Error fields and locked modes
  - size and field scaling
- NTM physics
  - direct stabilization; elimination of sawtooth seed
- ICRF heating/CD/flow: High field, weak single pass
- ICRF technology: load tolerance, antenna modeling
- Alfven Eigenmode physics
- AT physics toward steady state

B-scaling of Locked-Mode Threshold



C-Mod can study plasmas at the same β and magnetic field as ITER

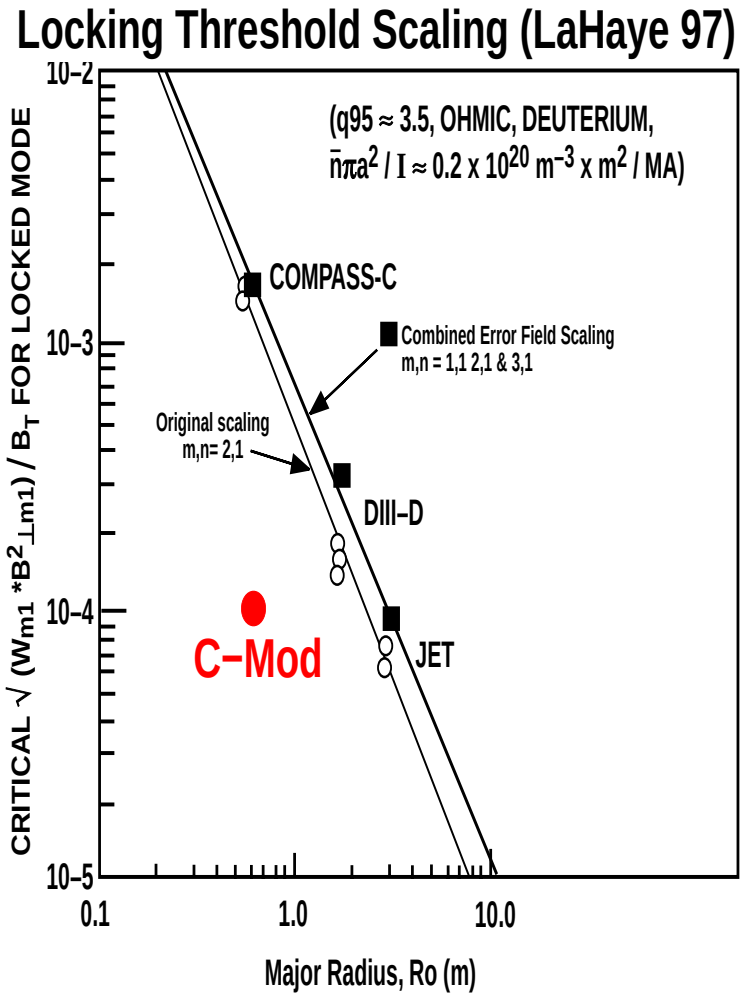


C-Mod Addressing High Priority ITPA Research Topics

- ITB and Transport
  - High performance with equilibrated electrons-ions
  - Impurity accumulation
  - Compatibility with edge conditions (density, small/no ELM regimes)
  - Test simulation predictions (GS2, gyro, BOUT)
- Important contributions to Confinement Databases (size, field)
- Pedestal and Edge
  - Pedestal structure (identity experiments, modeling)
  - Physics-based scaling
  - Small/no-ELM regimes
- Divertor and SOL
  - SOL plasma interaction with main chamber (pioneered at C-Mod)
  - Hydrogen retention processes (Metal PFC's)
  - Perpendicular SOL transport and boundary conditions

C-Mod Actively Participating in Joint Experiments Coordinated through ITPA

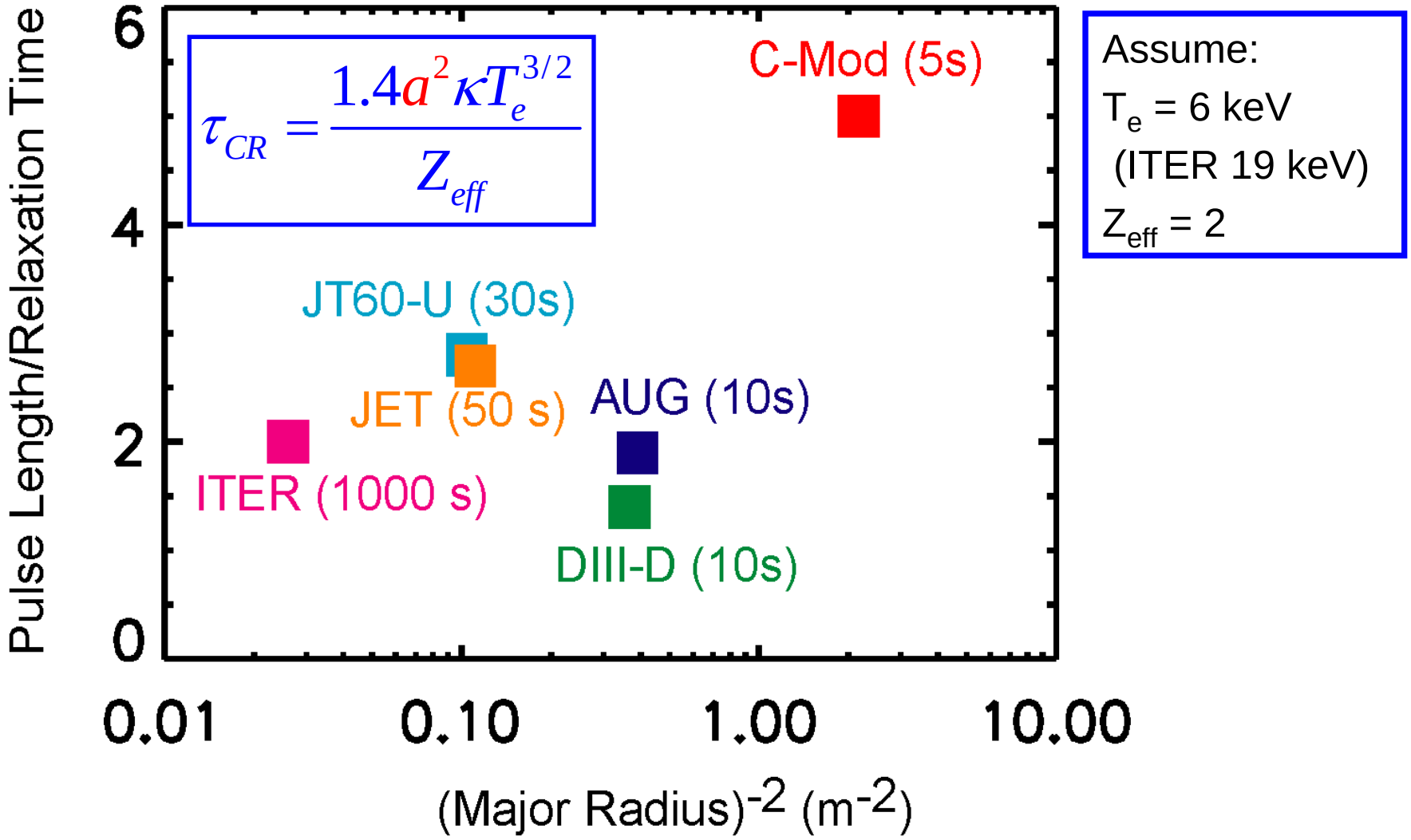
- Confinement scaling in ELMy H-modes (JET)
- Ohmic identity experiments: scaling with dimensionless parameters
- Transport properties of candidate hybrid scenarios
- High performance operation with $T_e \sim T_i$
- Enhanced confinement with low external momentum input
- Dimensionless identity pedestal experiments (JET)
- Dimensionless comparisons of L-H threshold and pedestals (ASDEX-U)
- Comparisons between C-Mod EDA and JFT-2M HRS
- Scaling of SOL radial transport
- Disruptions and effects on materials choices
- Role of Lyman absorption in the divertor
- Parallel transport in SOL
- Multi-machine study on separatrix density and edge profiles
- Deposition in tile gaps
- Pressure and size scaling of gas jet penetration for disruption mitigation
- NTM's including error field effects
- Error field sideband effects for ITER (C-Mod, JET, DIII-D identity experiments)
- Preparation of ITER steady-state scenario
- Preparation of ITER hybrid scenario



AT Physics: C-Mod Positioned to Study Fully Relaxed Current Profiles

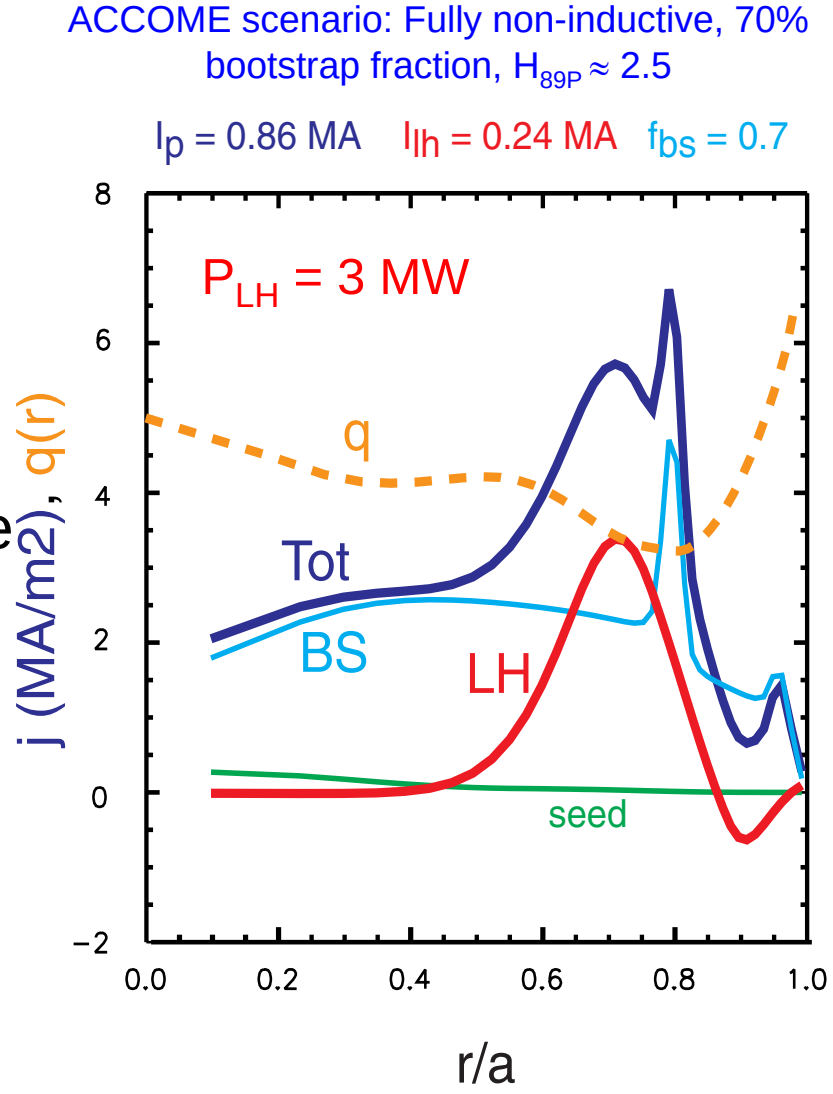
IPPA 3.1

- ***Normalized*** **pulse-length longer than any other operating high power divertor tokamak**



AT Operation likely needed for Successful ITER Quasi-Steady-State

- Requirements
  - Efficient off-axis current drive (r/a ≥ 0.7)
  - Confinement (control of edge + internal transport)
  - Impurity Control
    - L-mode or EDA/ELMy H-Mode edge
    - High heat-flux divertor
  - Efficient heating (ICRF + LH)
  - Density and density profile control
    - Active pumping, RF control

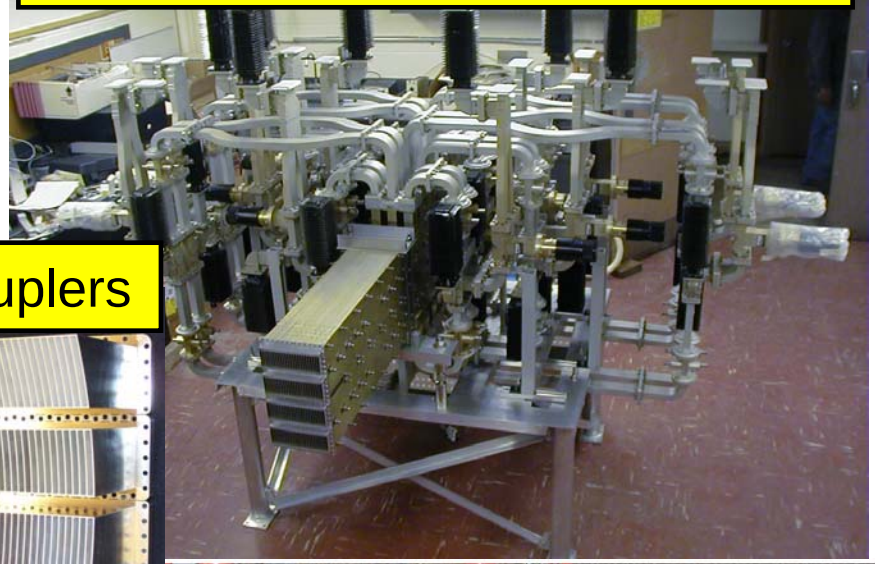


Lower Hybrid Current Drive Facility Upgrade
First Operation: Summer 2004

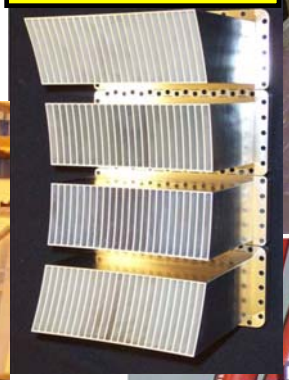
- Waveguide components assembled
  - Waveguides passed full power tests
  - Installation: May, 2004
- Major PPPL contributions

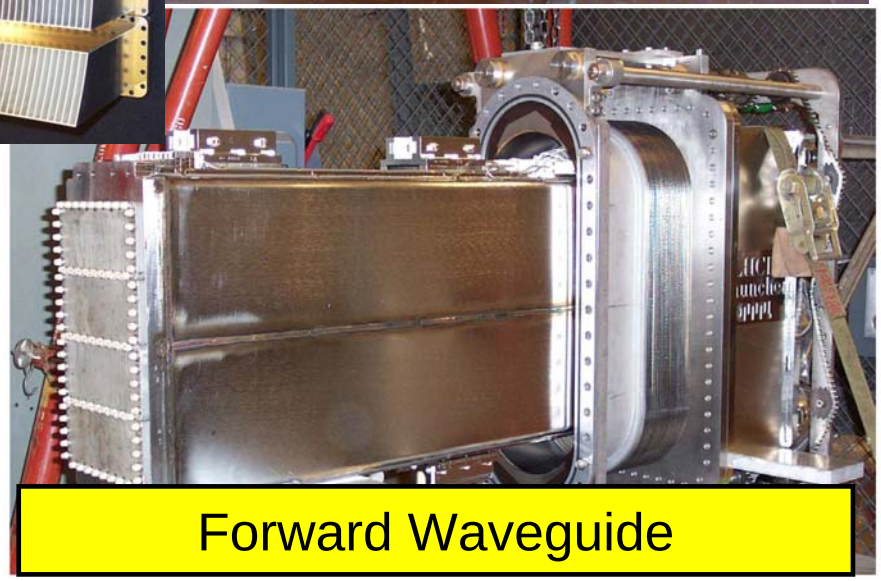
Klystrons (4.6 GHz, 3 MW)
Installed & Tested

Rear Waveguide



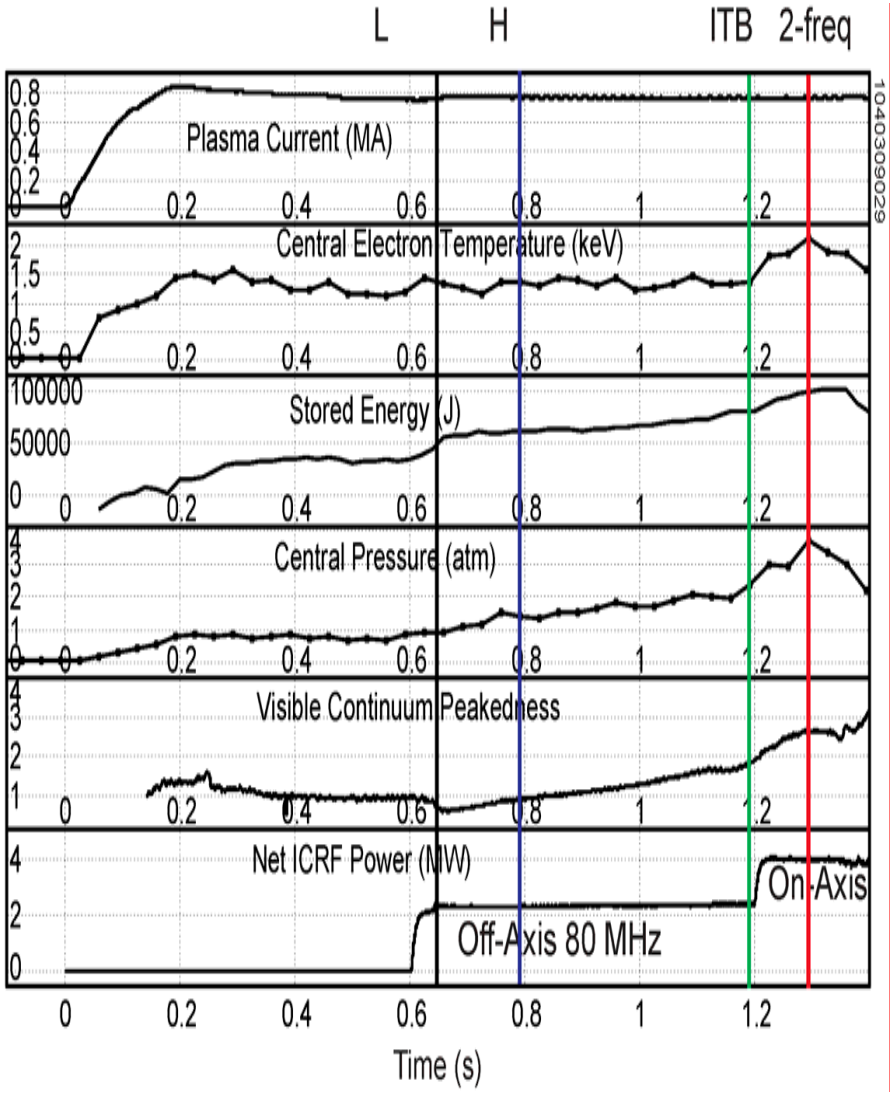
Couplers

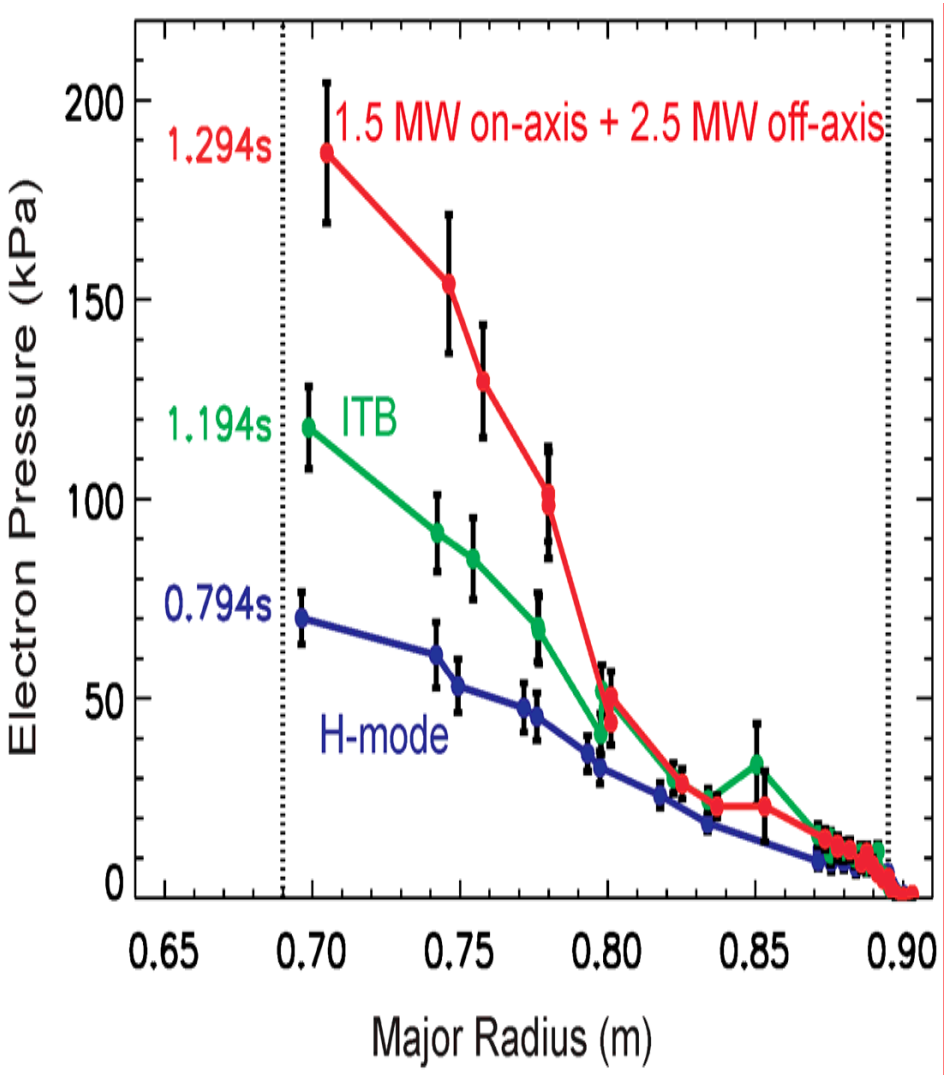




Forward Waveguide

ITB with strong on-axis heating leads to large core pressure gradients (P_0 ~ 4 Atmosphere)



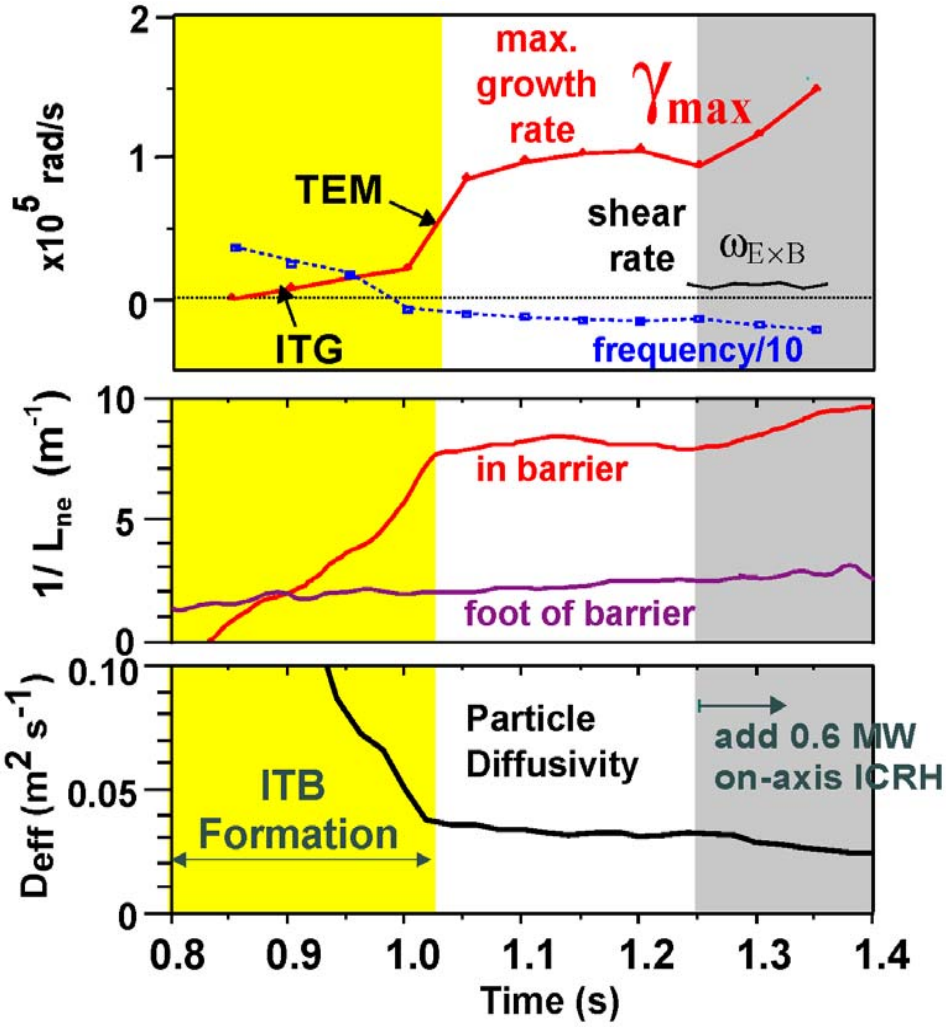


Transport: Areas of Focus

IPPA 1.1

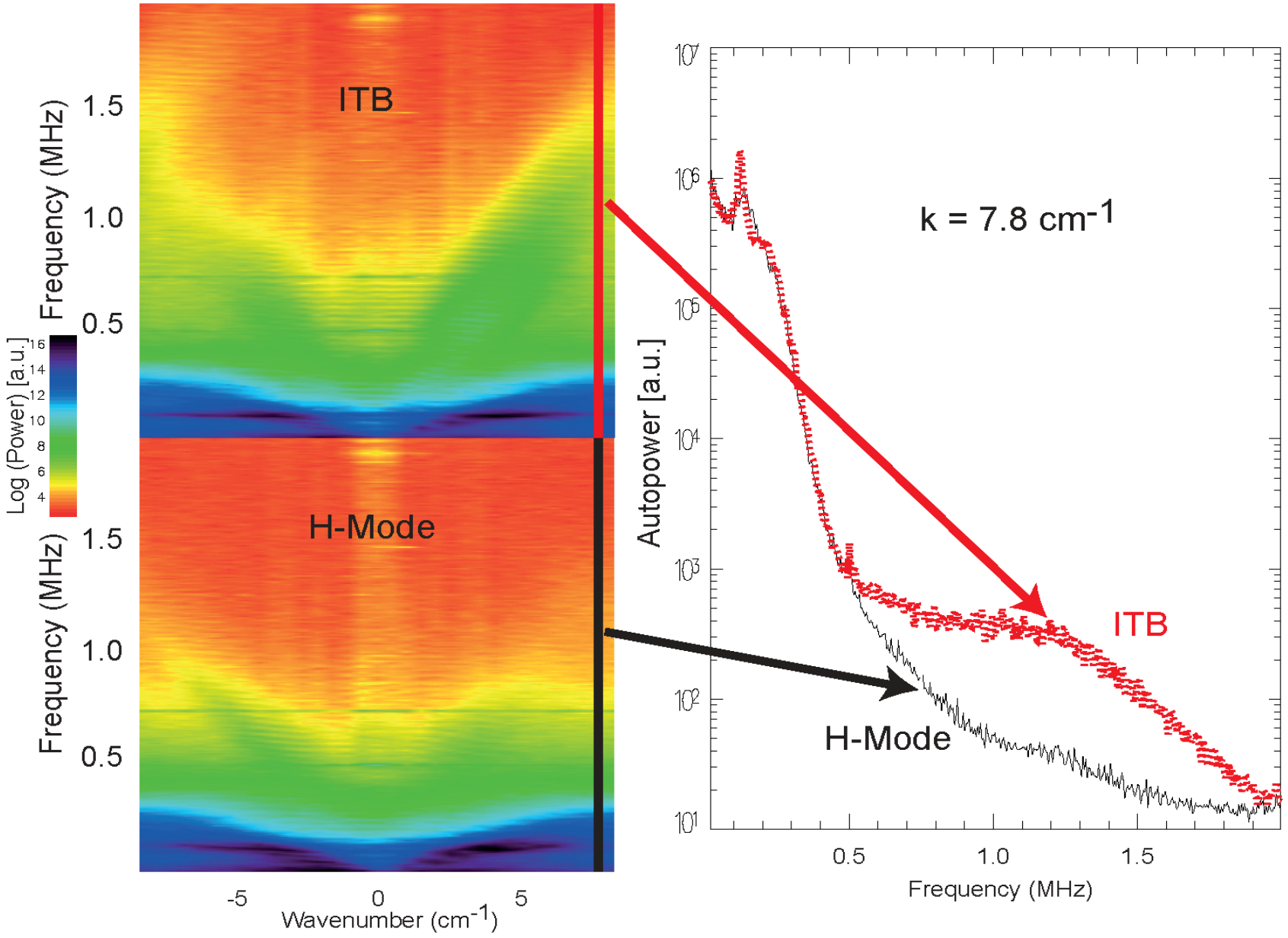
- Self-generated flows/momentum transport
  - Especially connections to L/H transition
- Access and control for ITBs in reactor-relevant regimes
  - Absence of core particle & momentum sources
  - Strongly coupled electrons-ions
  - Pulse length > skin time
- H-Mode pedestal
  - Width, gradient relaxation
  - Small/no-ELM regimes
- Particle transport
- Core Fluctuations
- Close and careful comparisons with theory/modeling in all areas

GS2 Modeling shows roles of ITG and TEM in formation and evolution of ITBs



Darin Ernst, et al., APS-DPP Invited (2003)

Phase Contrast Imaging Shows Growing High ν, High k Turbulence in ITB Plasma (TEM?)

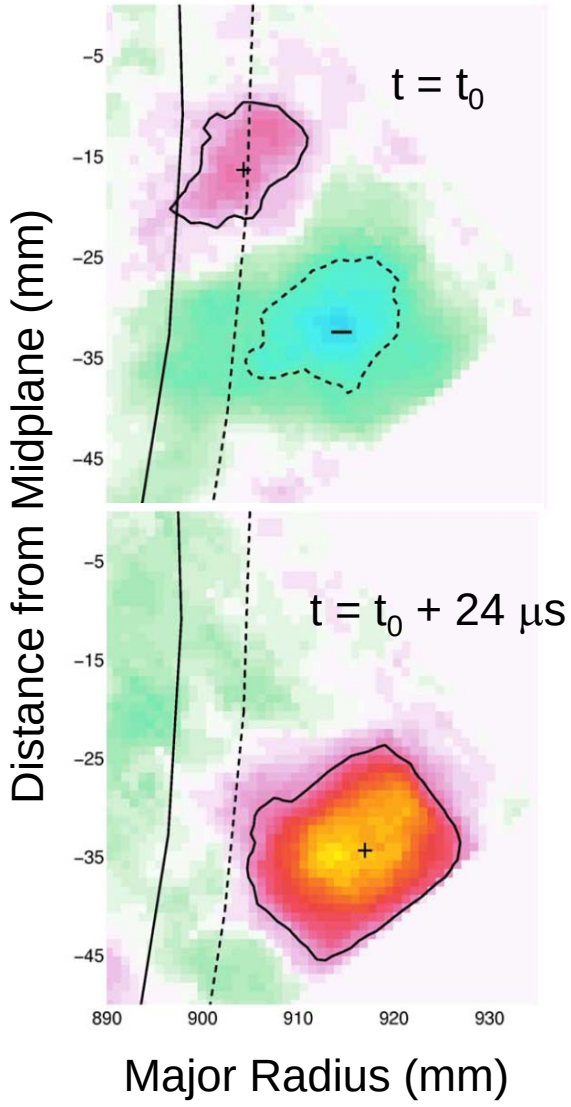


Science/Technology: Edge/Divertor

IPPA 1.4

- Edge Turbulence and Transport
  - Ballooning transport drives parallel flows
  - Turbulence dynamics
    - Filaments accelerate across SOL
    - Correlations support filament formation mechanism
  - Transport in the far SOL matched from C-Mod through DIII-D to JET
- Neutral Dynamics in high-Z PFC tokamak
  - Hydrogenic retention 100x lower than with C walls
  - Modelling of ITER-like C-Mod divertor finally close to experiment
- Power & Particle Control
  - Tungsten brush (ITER relevant)
  - New divertor configuration for optimized pumping

Evolution of Edge "Blobs"



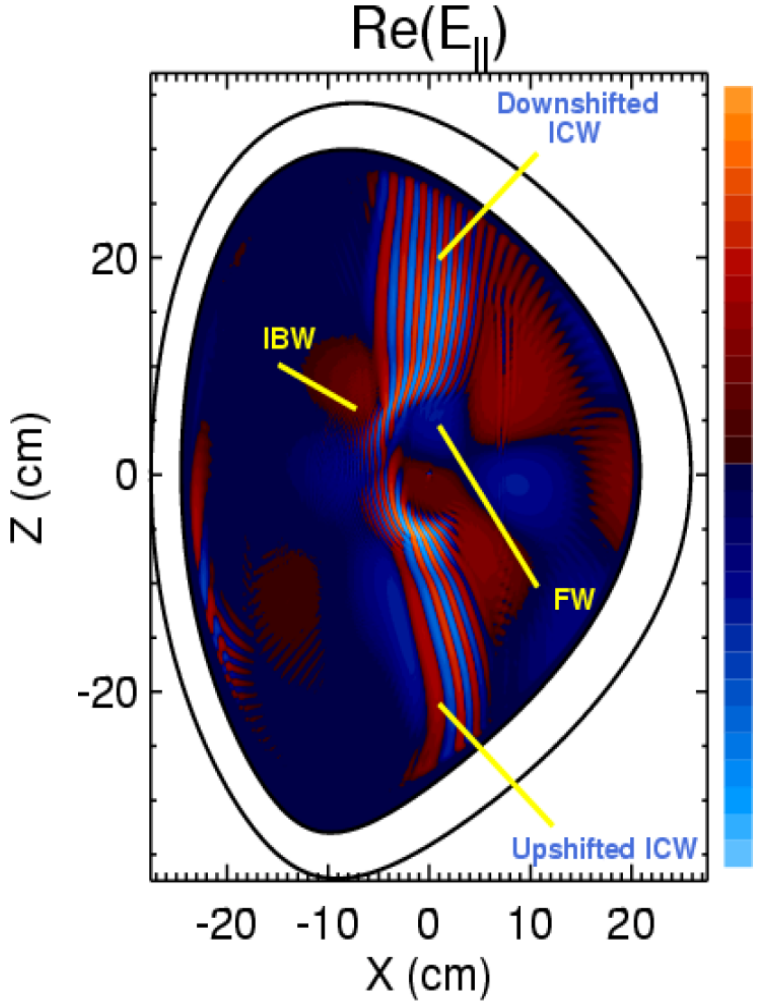
Olaf Grulke, et al., APS-DPP (2003)

Science/Technology: ICRF

IPPA 1.3

- High-Power Phased Antenna Operation
  - ITER technology development
- Weak single-pass (e.g. D(^{3}He)) scenarios
- Minority Ion-driven Alfven modes
- Mode Conversion
  - Flow drive
  - Current drive
- Sawtooth stabilization
  - Mode Conversion and Minority
- Unique core RF Diagnostic (PCI)
- Strong, integrated theory and modeling effort

Full-wave simulation of Mode-Conversion in C-Mod Discharge



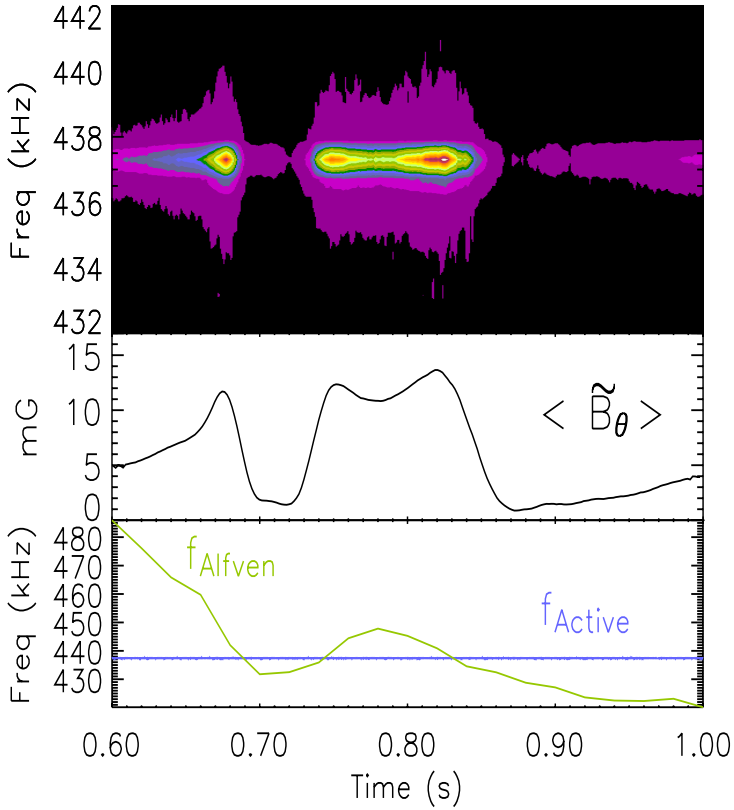
John Wright, et al., APS-DPP 2003 (invited)

MHD Stability Research

IPPA 1.2

- Disruption studies
  - Extend to 2 MA, 8 T
  - High pressure gas-jet mitigation
    - ITER-level plasma pressure
- Locked-modes: characterization and control
- Alfven and global modes
  - Probe stable modes with active MHD
- MHD at high β
  - NTM's, Core β-limiting modes
- Pedestal stability
  - H-Mode edge pedestal stability
  - Understanding ELM regimes:
    - comparisons with theory/simulation
  - Compare single/double null

Active MHD Probing of Stable Alfven Eigenmodes



Joe Snipes, et al., APS-DPP 2003

New Tools enable New Discoveries

- LHCD experiments begin in CY2004
  - 3 MW source @ 4.6 GHZ + 8 MW source ICRF (04)
  - 4 MW source @ 4.6 GHz + 8 MW source ICRF (07)
    - Add second LH launcher (06), new 4-strap ICRF antenna (07)
- New facility and diagnostic upgrades (partial list)
  - *Locked-mode coils*; Cryopump (n_e control); Divertor upgrades (advanced materials); Real-time antenna matching; Long-pulse DNB; High-P Gas Puff (disruption mitigation)
  - Hard X-ray imaging (LHCD); *Reflect. upgrades (higher n_e);* Polarimetry (j(r)); *CXRS upgrades;* PCI upgrades (*spatial coverage*, ρ_e scale); *Ultra-fast Imaging ($\tilde{n}, \tilde{T}$);* Erosion/deposition divertor diagnostics, *Neut. Part. Analyzer*

Implemented/Planned

Guidance Budgets Imply Significant Reduction in Facility Research Run Time

Alcator C-Mod

Guidance Budgets

Fiscal Year	2003	2004	2005	2006
Run Weeks	13	19	**14**	**12**
Run Hours	400	600	**450**	**390**

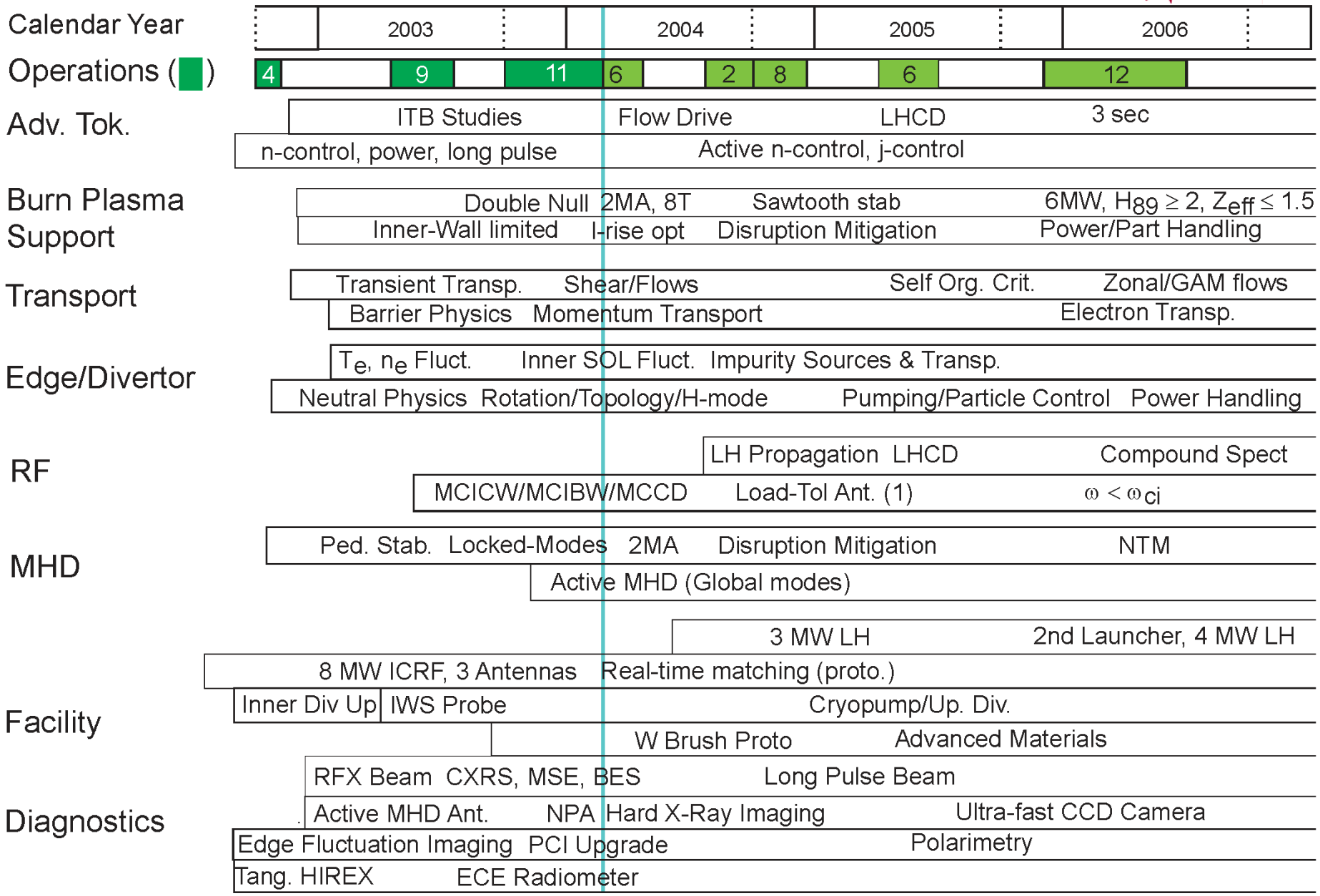
10% Increment in 2005

Fiscal Year	2003	2004	2005	2006
Run Weeks	13	19	**21**	**18**
Run Hours	400	600	**670**	**600**

10% Decrement in 2005 or 2006:

Fiscal Year	2003	2004	2005	2006
Run Weeks	13	19	**11**	**10**
Run Hours	400	600	**350**	**320**

Alcator C-Mod
Overview Schedule (March 2004)



Research Goals (FY04-FY06)

Plasma flow control with radio waves (MC-ICRF)	SEP 2004
Sensing approach to instability using active coils	SEP 2004
Commissioning of the microwave current drive system (LHRF)	SEP 2004
Driving electric current with radio waves (MC-ICRF)	SEP 2004
Power and particle handling for Advanced Tokamak plasmas	SEP 2004
Current profile control with microwaves (LHCD)	FY 2005
Sustaining plasma current without a transformer	FY 2006

Highest Priority Upgrades Included in Guidance Budgets (FY05-06)

- Cryopump (density control for AT, lower ν for BPX support)
- Correction coil supply upgrades (Error field comp.)
- LHCD:
  - Construction, installation of second launcher
  - Add 4th MW
- ICRF real-time matching (1 antenna only)
- New Diagnostics and Upgrades
  - Thomson scatt., Polarimetry, IR imaging, core and edge turbulence
- DAC infrastructure upgrades (data collection doubling time ~2 years)

Consequences of 10% Cut (FY2005)

- 3 week reduction in research operation (to 11)
- Personnel cuts:
  - 1 scientist, 2 engineer, 2 technicians, 1 student
- Critical upgrades deferred
  - LHCD
  - Advanced 4-strap ICRF antenna
  - Outer divertor upgrade (power handling)
  - Polarimeter/Interferometer (j(r) at high density; ITER geometry)

Highest Priority Increments (FY05B)

- Improved utilization: 7 additional weeks research operation (to 21 total) (1500k)
- 4-strap ICRF antenna to maintain full capability with additional LHCD launcher (350k)
- Spare 4.6 GHz Klystron (currently 1 spare, 16 klystron system) (500k)
- Core Thomson scattering upgrade (spatial channels) (150k)
- Active MHD upgrade (toroidal mode number control) (50k)
- ICRF real-time matching (2^{nd} antenna) (350k)
- Outer divertor upgrade (power handling >8MW, 5 s) (200k)
- Full utilization: 4 additional weeks research operation (to 25 total) (900k)

Consequences of 10% cut in FY06

- 2 week reduction in research operation (to 10)
- Further personnel reductions
  - 1 Engineer, 1 Tech, 2 Scientists, 1 Student
- Reduced pace for LHCD upgrades
  - at least 6 month delay in implementation
- Polarimeter deferred
- Tungsten divertor delayed
- Real-time ICRF matching deferred
- Outer divertor upgrade delayed

Highest Priority Increments (FY06B)

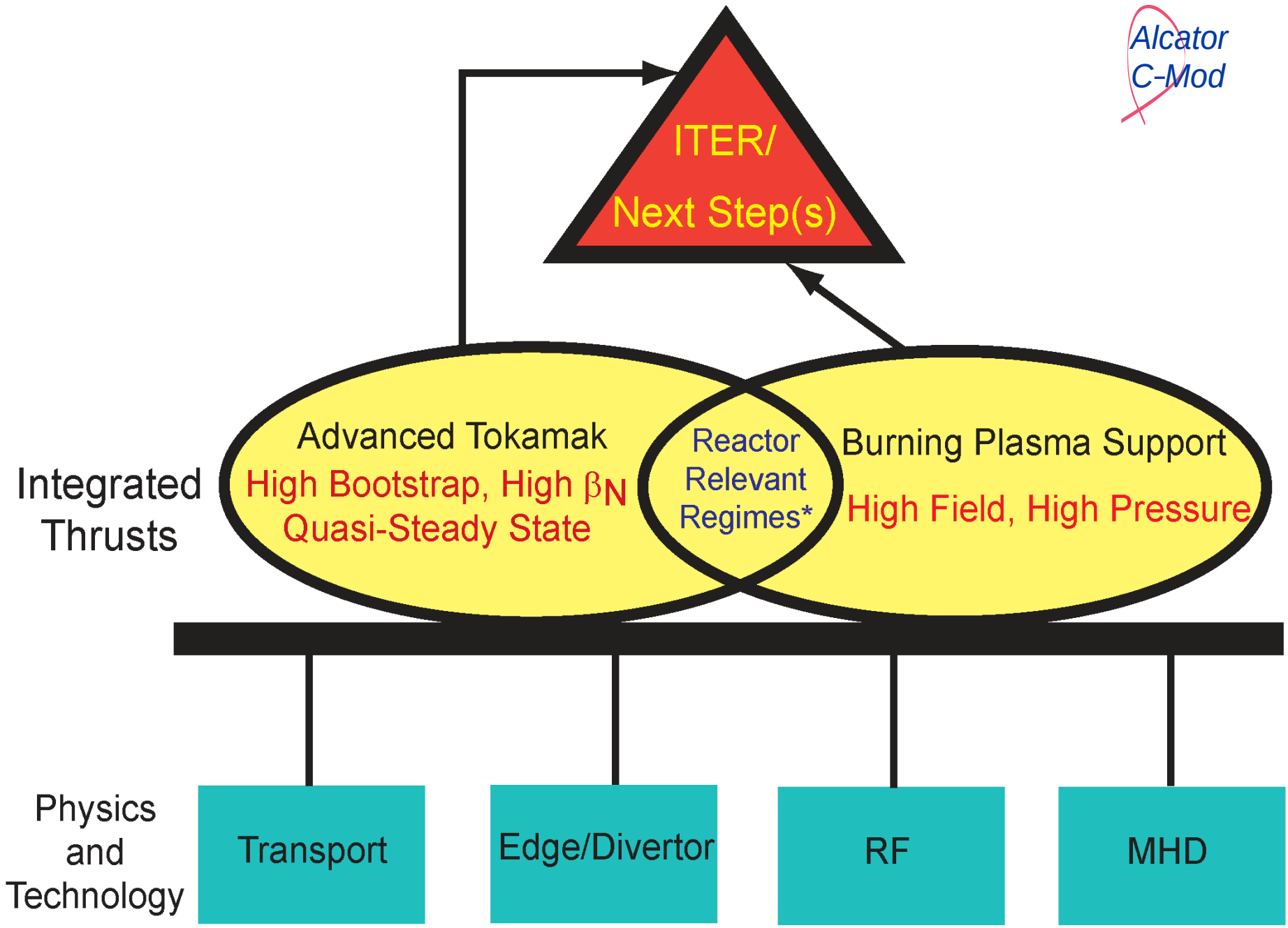
- Add 6 weeks of research operation, to 18 weeks (1400k)
- 4-strap antenna (complete and install to maintain full capability (400k)
- Spare 4.6 GHz klystron
- Add 3 weeks research operation, to 21 weeks
- High resolution x-ray diag upgrades (additional tangential views) (100k)
- Complete outer divertor upgrade (300k)
- Complete ICRF real-time matching (350k)
- Add second view for MSE (direct E_r) (400k)
- ICRF cavity conversions (fixed to tunable) (350k)
- Advanced material divertor (ITER/BP tungsten) (500k)
- Core fluctuation scattering diag (complete in FY07) (300k)
- Full utilization: add 4 weeks research operation, to 25 weeks (950k)

C-Mod National Budgets (k$, Mar 2004 Guidance)

	FY04 Approp	FY05A Guidance	FY05B Prog Plan	FY06A Level	FY06B Prog Plan
Research	5,950	5,969	6,631	5,969	7,278
Operations	13,344	12,500	16,234	12,500	17,486
Capital Equipment	190	307	399	307	407
International Collaborations	47	47	47	47	47
MDSplus	146	149	149	149	149
PPPL Collaborations	2,070	2,050	2,250	2,050	2,250
U. Tx. FRC Collaborations	425	425	480	425	480
LANL Collaborations	97	100	120	100	120
Alcator Project Total	**22,269**	**21,547**	**26,310**	**21,547**	**28,217**

Alcator C-Mod Summary National Budgets, Run Time and Staffing

		FY04 Approp	FY05 Guidance	FY05 Prog Plan	FY05 -10%	FY06 -10%	FY06 Flat	FY06 Prog Plan
Funding ($ Thousands)								
Research		5,950	5,969	6,631	5,622	5,622	5,969	7,278
Facility Operations		13,344	12,500	16,234	11,000	11,000	12,500	17,486
Research Capital Equipment		190	207	299	186	186	207	307
Operations Capital Equipment		0	100	100	90	90	100	100
PPPL Collaborations		2,070	2,050	2,250	1,845	1,845	2,050	2,250
UTx Collaborations		425	425	480	383	383	425	480
LANL Collaborations		97	100	120	90	90	100	120
International Activities		47	47	47	42	42	47	47
MDSplus		146	149	149	134	134	149	149
Total (inc. International)		**22,269**	**21,547**	**26,310**	**19,392**	**19,392**	**21,547**	**28,217**
Staff Levels (FTEs)								
Scientists & Engineers		49.38	48.93	54.43	45.73	44.73	48.43	52.64
Technicians		30.28	28.28	32.28	26.08	24.28	26.28	32.58
Admin/Support/Clerical/OH		16.27	15.46	17.08	13.91	13.82	15.33	17.24
Professors		0.25	0.25	0.25	0.25	0.25	0.25	0.25
Postdocs		2.00	3.00	3.00	3.00	2.00	3.00	3.00
Graduate Students		22.05	22.05	22.05	20.05	19.00	22.05	22.05
Industrial Subcontractors		1.20	1.00	1.00	1.00	1.00	1.00	1.00
Total		**121.44**	**118.98**	**130.10**	**110.03**	**105.09**	**116.35**	**128.77**
	FY03 Actual	FY04 Approp	FY05 Guidance	FY05 Prog Plan	FY05 -10%	FY06 -10%	FY06 Flat	FY06 Prog Plan
Facility Run Schedule								
Scheduled Run Weeks	13	19	14	25	11	10	12	25
Users (Annual)								
Host	53	56	54	60	53	51	53	60
Non-host (US)	90	95	93	110	90	85	90	95
Non-host (foreign)	10	12	10	18	10	10	10	18
Graduate students	24	25	24	26	23	21	24	26
Total Users	**153**	**163**	**157**	**188**	**176**	**167**	**153**	**173**
Operations Staff (Annual)								
Host	68	71	69	80	66	65	67	80
Non-host	4	4	4	5	4	3	4	5
Total Operations Staff	**72**	**75**	**73**	**85**	**70**	**68**	**71**	**85**



*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive